THE EFFECT OF ACCELERATION ON THE BURNING RATE OF DOUBLE BASE ROCKET PROPELLANTS

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THESIS

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ABSTRACT

Double base rocket propellants with and without aluminum were burned in a centrifuge at two pressures and nine accelerations. The burning rates were measured to isolate the effect of the aluminum.

The burning rate of the non-aluminized propellant was found to vary with acceleration and a model was advanced. The addition of aluminum causes an increase in burning rate at higher accelerations and a possible mechanism is discussed.

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ACKNOWLEDGEMENTS

The author would like to acknowledge the invaluable assistance of Mr. Edward Michelson with the experimental equipment, and especially his advisor and co-worker, Dr. David Netzer.

I. INTRODUCTION

The performance of solid propellant rocket motors has been known to deviate considerably from their static values when used operationally in high-acceleration environments. Typical results are higher chamber pressures (sometimes resulting in motor failure), shorter burn times and lower total impulses.

Because of this several studies [references 1, 2, 3, 4] were initiated at the Naval Postgraduate School in Monterey, to isolate the effect of the various parameters involved. One of the most important parameters is the metal content, usually aluminum.

Most of the studies have involved aluminized composite propellants, composed of a powdered oxidizer such as ammonium perchlorate suspended in a plastic fuel matrix. Aluminum may be added to increase the heat content and thus the specific impulse.

Sturm [1] reported the burning rate augmentation of composite propellants at a fixed pressure and acceleration to depend on the mass fraction of the aluminum and its mean-particle size and the mean-particle size of the oxidizer.

In order to help further isolate the effect of the aluminum, the present study was initiated using a propellant without oxidizer particles. It was hoped that the burning rate augmentation would depend only on the aluminum content. Since the aluminum content would be the only acceleration sensitive parameter, the applicability of theories on the burning rate augmentation due to aluminum additives could be tested.

To this end two types of propellants were employed. One was a standard double-base propellant consisting of a homogenous mixture of nitroglycerin and nitrocellulose with a small percentage of stabilizers. The other was an identical double-base propellant with the inclusion of approximately 5%, by weight, aluminum.

Tests were run at pressures of 500 and 1000 psia using conventional strand-burning techniques on a 76-inch diameter centrifuge. Burning rate augmentation of the two propellant types was measured at acceleration levels of up to 1000g's.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. EQUIPMENT

1. General

This study is the fourth in a series of burning rate studies at the Naval Postgraduate School centrifuge test facility located at the rocket test laboratory. The equipment was designed and built by J. Anderson [2,3]. Reference 3 gives a detailed description of the facility. This chapter contains only a summary to orientate the reader.

2. Centrifuge

The centrifuge was designed to subject the combustion bomb to accelerations of up to 2000 g's. The 76-inch nominal diameter of the centrifuge was chosen to provide as low a change in acceleration with burned length of the strand as possible without exceeding the power available. For the 2-inch strands used in this study the variation of the G level amounts to approximately 7%.

The power for the centrifuge is provided by a standard 6-cylinder Chevrolet engine coupled through a power glide transmission (see Plate 1).

The combustion bomb is located at the end of one of the centrifuge arms and is capable of maintaining a pressure of up to 3000 psia for the burning rate experiments. The bomb has an internal volume of 115 cubic inches. As the propellant sample burns, a large volume of hot gases are evolved. In order to reduce the pressure rise above

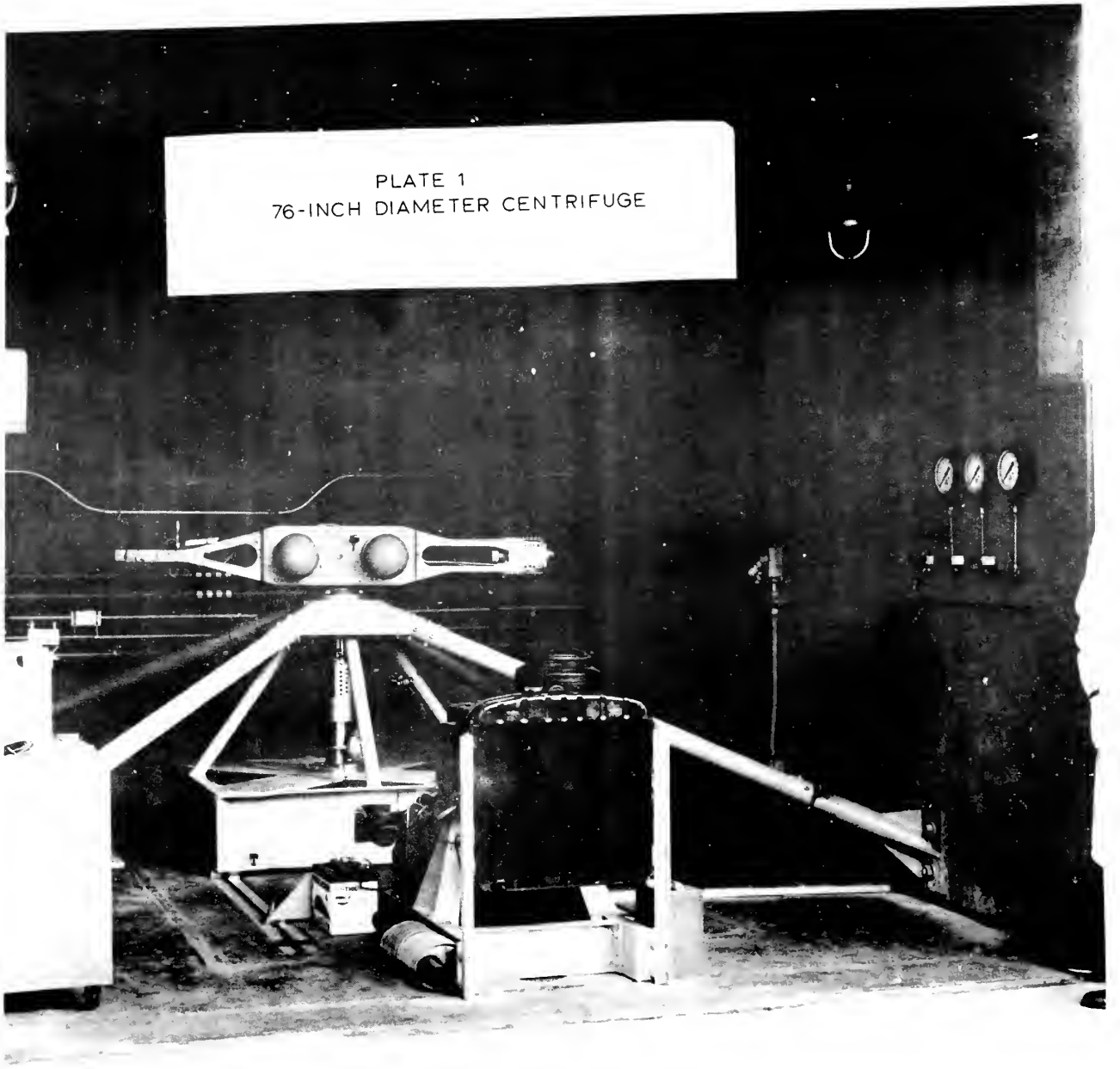

PLATE 1
76-INCH DIAMETER CENTRIFUGE

its initial value two aluminum surge tanks of 725-cubic inches volume each, are mounted near the center of the rotor. These surge tanks are connected to the bomb through a 3/8-inch stainless steel line. An isolation valve is provided to allow depressurization of the bomb without loss of the pressure in the surge tanks. This results in a considerable saving on the nitrogen gas consumed. The bomb-surge tank system is charged through a Bruning Magnum quick-disconnect valve "T"ed into the interconnecting line. The pressure transducer used to produce the time-pressure traces is mounted on the center line to minimize the zero shift due to acceleration. The transducer is connected to the bomb through a separate 1/4-inch stainless steel line that also contains the discharge valve. A solenoid valve which was originally tied into this line was removed due to its poor operation and replaced by its equivalent weight.

A counterbalance is mounted on the opposite end of the rotor from the bomb. Various weights are placed in this to provide the proper static balance. The bearings of the centrifuge can take a maximum load of 500 pounds which means an imbalance of 1/4 pound at maximum acceleration of 2000 g's. In practice the imbalance is far smaller than this. Even the small imbalance due to different pressures in the bomb are counterbalanced. Plate 2 shows the rotor and associated components.

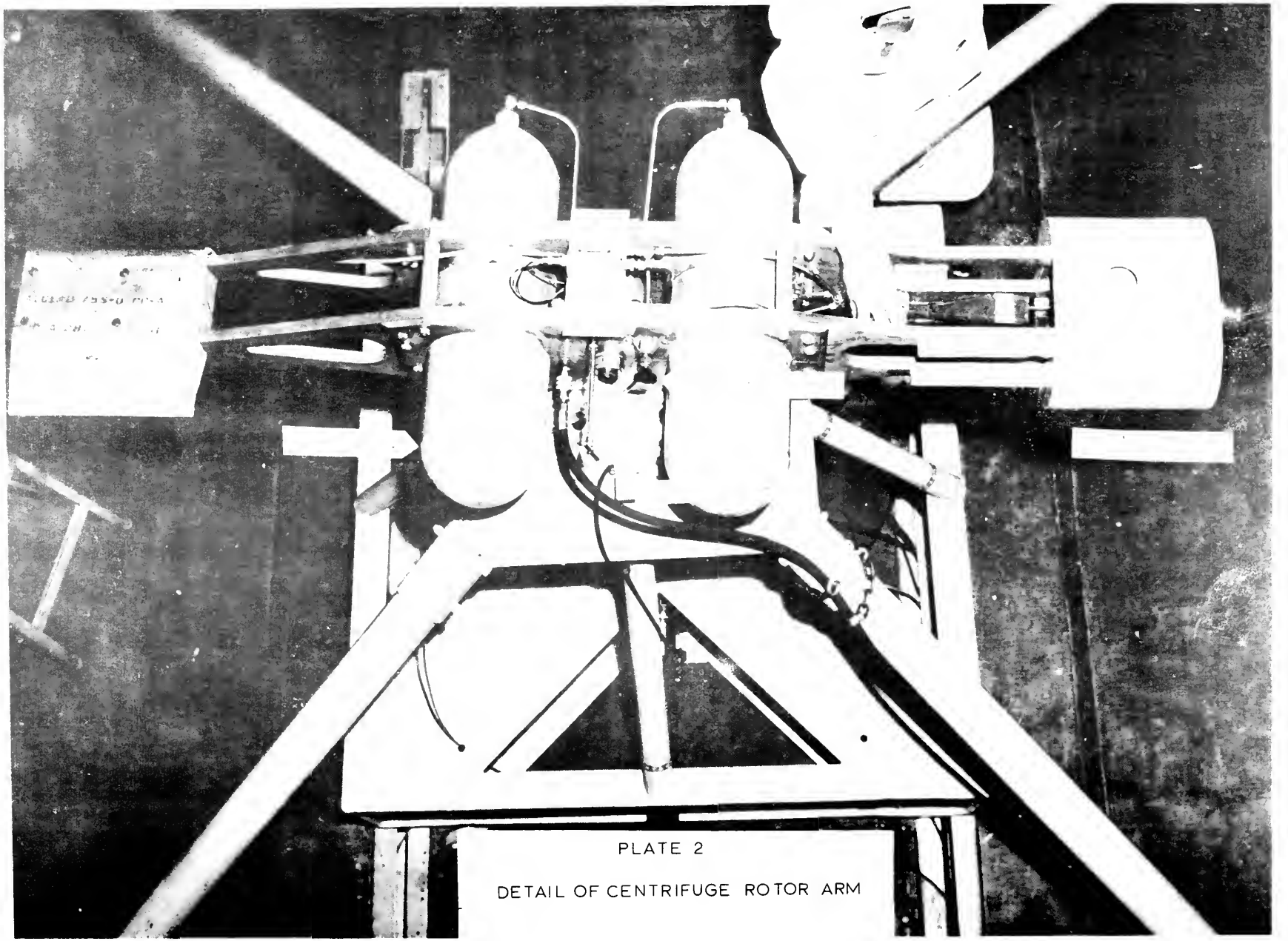

PLATE 2

DETAIL OF CENTRIFUGE ROTOR ARM

3. Instrumentation

The engine control console contains the remote throttle and a Berkeley model 5545 Eput meter indicating centrifuge rotation speed. The Eput meter receives its signal from a Spaco-type PA-1 Magnetic pickup mounted on the drive shaft. The Eput output is $(\frac{RPM}{2})$ or N, which is used to determine the acceleration level.

The rotor instrumentation consists of a Daystrom-Wiancko 4000 psig-range type P2-3086 variable reluctance pressure transducer and timing wires. These outputs and the igniter input pass through a Lebow model 610a-12 instrumentation slip ring assembly mounted below the centrifuge. The pressure-sensing and recording circuit is shown in Plate 3. In order to more easily determine the average pressure and locate the ignition and burn-out times, the initial bomb pressure signal was cancelled using a 22 volt dry cell and a potentiometer. The amplifier output was set to give the expected transducer output roughly half-scale deflection on the oscillograph used to record the signal. Power for the transducer is supplied by a model 3509 transistorized power supply from Systems Research Corporation. The output amplifier was an Astro Data model 885 wide band differential type. The oscillograph was a Honeywell Visicorder model 1508. The time base was a 20 Hertz external signal imposed on the Visicorder from a Hewlett-Packard model 211A square-wave generator. The timing wires,

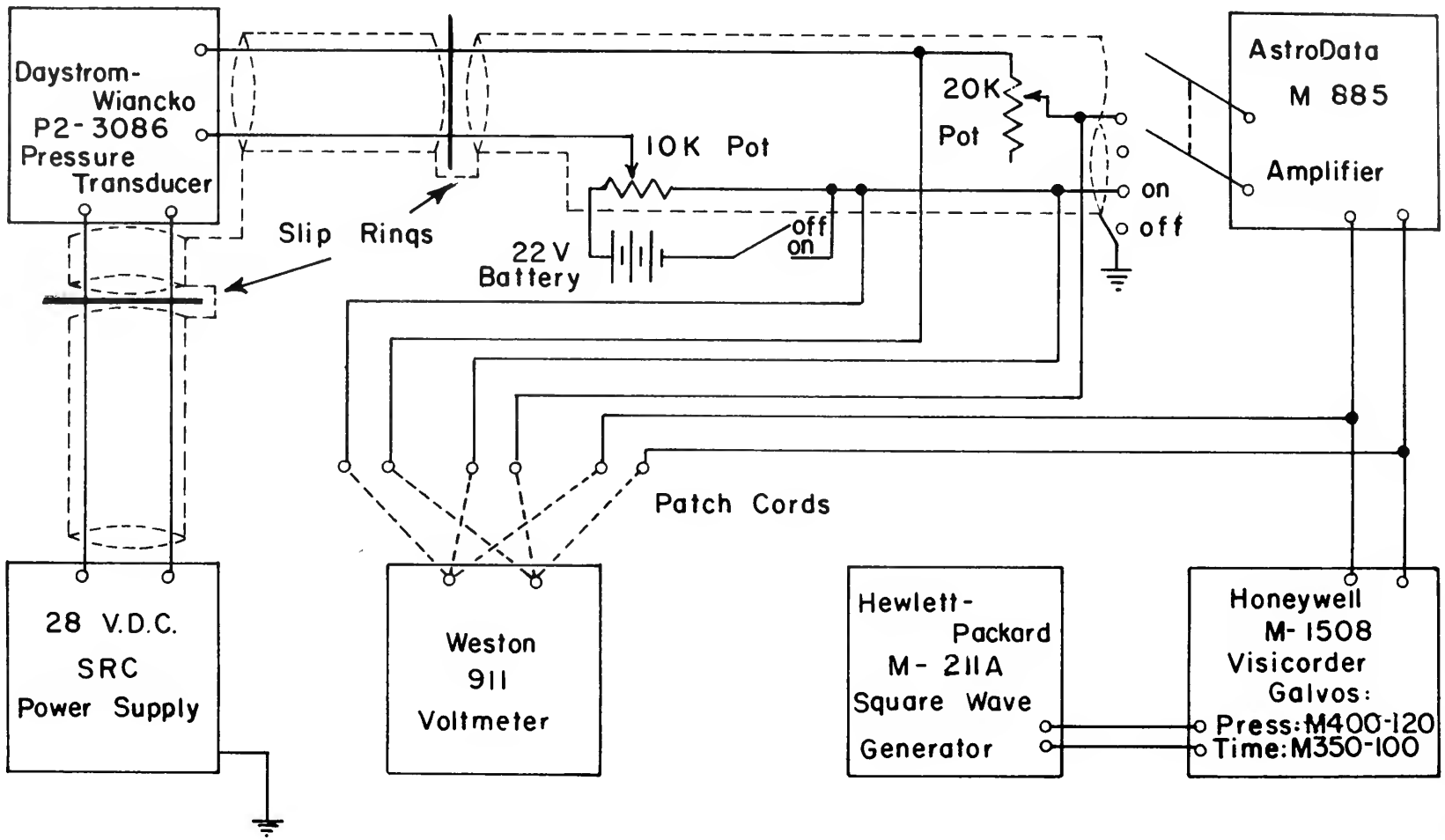

PLATE 3

PRESSURE SENSING AND RECORDING CIRCUIT

which indicate the passage of the burning surface by melting and opening the circuit, were not used in this study since good results were obtained from the time pressure traces. The timing wire, ignition and continuity test circuits are detailed in Plate 4.

4. Strand Holders

The propellant samples are held in place in the combustion bomb by means of the strand holders. The strand holders used in this study were only slightly modified from those used by Sturm [1] and Anderson [2, 3]. According to Bringhurst [4] the most practical size propellant samples are 1/2 by 1/2-inch in cross section. This size allows the best correlation with results of other experimental work without giving undue pressure rise in the bomb. With the inhibitor cast around the strands they measure approximately 3/4 by 3/4-inch.

The strand holder consists of a machined aluminum plug making a pressure seal with the bomb by means of an "O-ring." The outer end of the plug is flared to provide a metal-to-metal seat to prevent the extrusion of the "O-ring" under high accelerations. The wiring comes out of the bomb through a conax MTG-20-A-4-T gland seal. Above the gland seal is a miniature fire-pin connector. Additional pressure sealing is provided by saturating the high-pressure side of the wire passages with high-temperature APCO #210 EPOXY Resin. Where the wires run along the back of the strand holder slab, they are also covered with this resin to protect them from the high-temperature

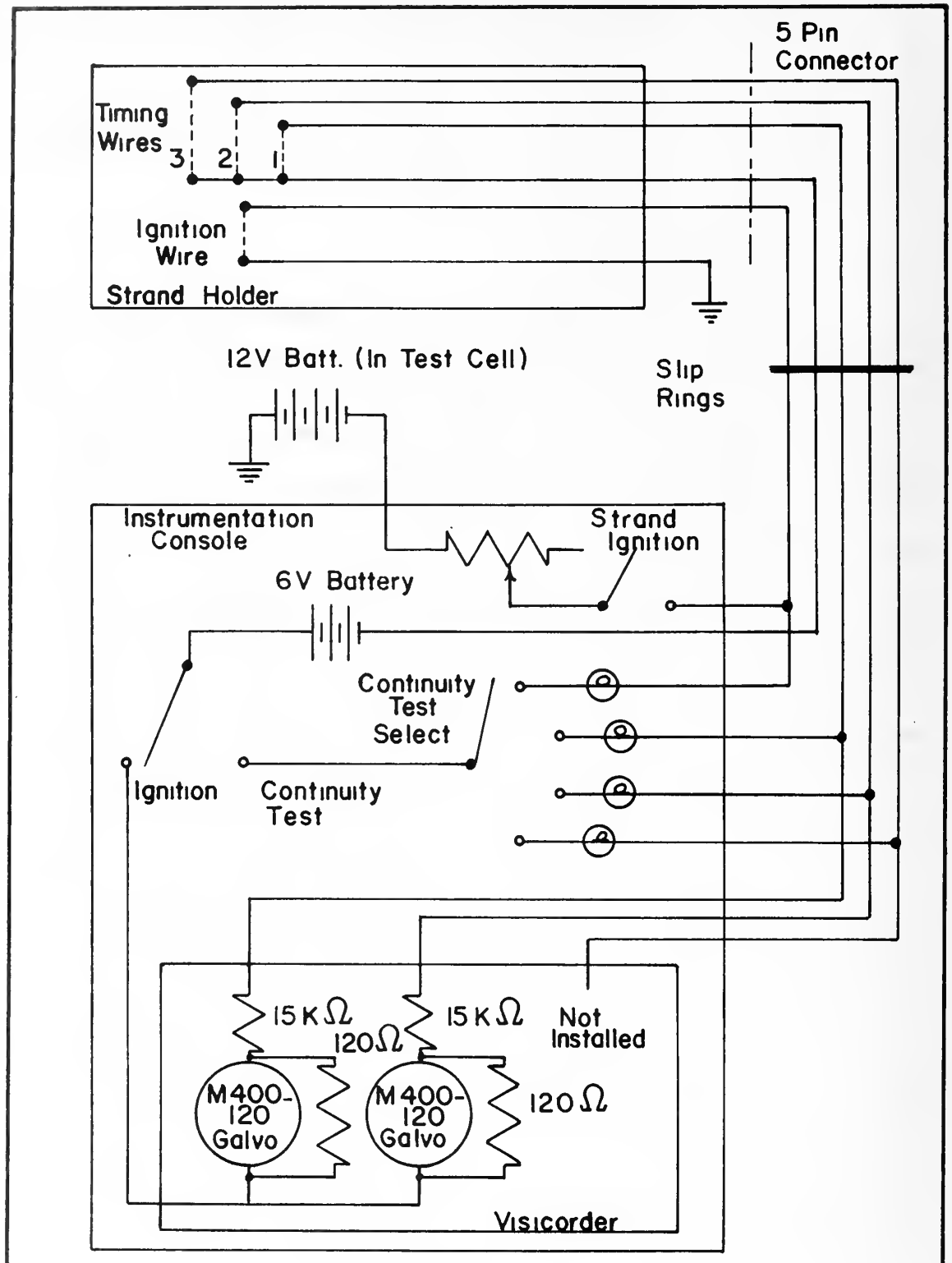

PLATE 4

TIMING WIRE, IGNITION AND CONTINUITY TEST CIRCUITS

gases. Structural support for the strand is provided by a canvas phenolic slab. The slab contains the ignition and timing wire terminals. The slab is shielded from the hot gases by a phenolic insulation sheet. Plate 5 details the construction of the strand holder.

5. Nitrogen-Charging System

Upstream of the flexline used to charge the bomb-surge tank system is the nitrogen-charging station. Two pressure gauges were available for measurement of the bomb pressure. Valving was used to select the more sensitive gauge for the given pressure interval.

B. PROCEDURES

The procedures used in this study were identical with those used by Sturm [1] and Anderson [2, 3].

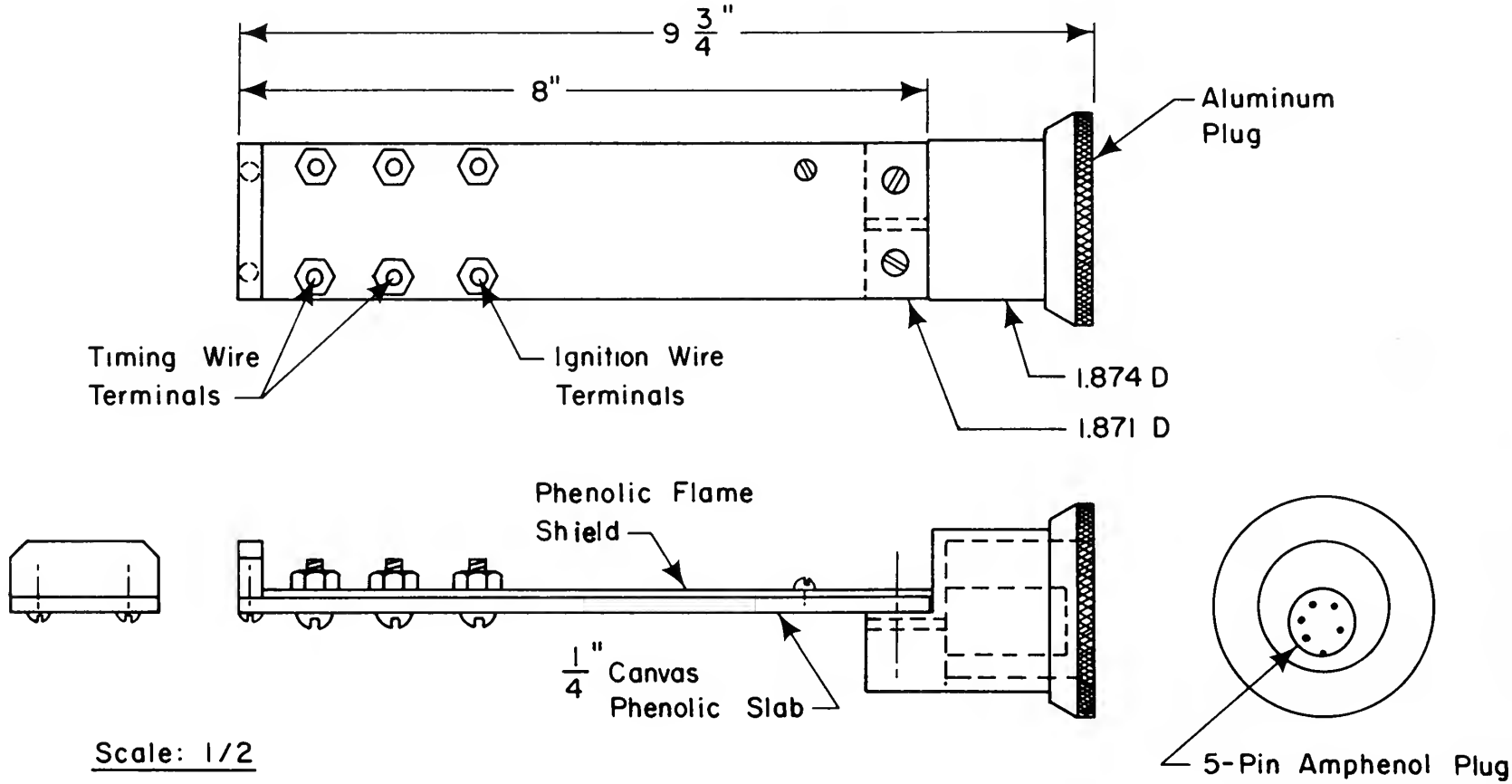

PLATE 5

STANDARD STRAND HOLDER

III. PROPELLANTS, STRAND PREPARATION AND DATA REDUCTION

A. PROPELLANTS

Two types of propellants were used in this study. One was standard double-base propellant containing 2 1/2% monobasic lead and 2 1/2% monobasic cupric salicylate. The bulk of the propellant was a homogenous mixture of nitroglycerin and nitrocellulose.

The second propellant was identical to the first except the total amount of nitroglycerin and nitrocellulose was reduced by approximately 5% to allow the addition of that weight in aluminum. The particle size and distribution of the aluminum was unavailable from the supplier. Both propellants contained the same amount of lead and copper salts, that are used as burning rate stabilizers.

B. STRAND PREPARATION

The propellant samples came in an assortment of sizes and shapes. A band saw was used to cut the propellant into 1/2 x 1/2-inch section strands. The initial lengths were 3, 6, 7 1/2 and 10 inches, depending on the parent block

To assure end burning of the propellant the sides were inhibited. In order to cast the inhibitor around the strands a mold was made of General Electric RTV 630-molding silicone plastic. The mold contained 3/4-inch wide by 3/4-inch deep patterns in lengths of 3, 6 and 10 inches. The last 1/2 inch on either end contained a step 1/8 inch above the bottom of the pattern. The propellants were rigid enough to be

supported from either end without noticeable deflection. Thie allowed casting the inhibitor completely around the strand in one pouring. The inhibitor used was Selectron 5119 resin manufactured by the Pittsburgh Plate Glass Company. The catalyst used was methyl ethyl keytone peroxide in a solution of dimethyl pthalate, known as Garox and made by the Ram Chemical Company, Gardena, California. The Selectron and catalyst were mixed in the weight ratio of 25 to one. After mixing, the inhibitor was poured down one side of the mold and allowed to flow under the strand and up the other side, thus preventing air (bubbles) from being trapped under the strand.

After the inhibitor had cured, the strands were removed from the mold and inspected for bubbles. The only difficulty with air bubbles occurred when the pouring method described above was not used. The strands were cut to the desired size on the band saw. After the first firings and the short burn times associated with one-inch strands it was decided to use 2-inch strands exclusively for this study to increase the accuracy of determining burning rate. After cutting the strands they were measured to within 0.001 inch and labeled as to type of propellant. On a master sheet this label was recorded with the length of the sample. Next, a 1/4-inch thick cap of inhibitor was cast on the end of the strand forming a small end-burning rocket motor. To prepare the strand for mounting, notches were cut in the inhibitor case for the igniter wire. The igniter wire must <u>not</u> cross the propellant surface where it may melt and fall onto the burning propellant. The wire must run along the

inhibitor wall and the notches are to keep it from moving. The strand was next secured to the strand holder with masking tape. The igniter wire was run from terminal to terminal through the notches in the case. The exposed surface of the propellant and the igniter wire were coated with a mixture of Tester's Household Cement and black powder to ignite the whole surface.

The cement used was found to be very critical. Results with Tester's Airplane Cement as an igniter binder were very poor; burn-out time was indeterminate. Experiments were run to determine the linear burning rates of the black powder with the two glues. Batches of each were mixed and spread over a length of approximately 1/2 foot. The Tester's Airplane Cement burned erratically and required several seconds to cover the distance. The Tester's Household Cement batch seemed to flash over the whole distance. The pressure time traces of strands ignited with the household-type igniter mixture had a well-defined burn-out point. This ignition method was further verified by using two igniter wires on either side of the strand. No difference in the burning time or pressure traces were observed. It was therefore assumed that the entire upper surface of the propellant was ignited within a few hundreths of a second.

C. DATA REDUCTION

1. Acceleration

The lowest acceleration used in this study was 50 g's. At this level the contribution due to the vertical component gravity is negligible. The acceleration was therefore assumed to be purely radial. The magnitude of the acceleration in g's was computed as:

$$G = N^2/247.5$$

N is the centrifuge RPM/2. This equation is based on the 35.6-inch radius to the center of a mounted 2-inch strand. The centrifuge speed was set to a value given by the inverse equation:

$$N = 15.72(G)^{1/2}$$

Where G is the desired acceleration level

2. Burning Rates

The burning rates were determined by dividing the length of the strand by the burning time. The burning time was determined by counting the number of cycles of the external timer to the nearest 1/4 cycle between ignition and burn out. Ignition was assumed to occur at the point where the extended pressure trace, less the igniter "pip", intersected the initial pressure. Plate 6 gives a typical time pressure trace.

The mean bomb pressure was found from the pressure time trace by graphical integration. After a series of runs the cases were inspected; any residue removed and weighed, and notes were made on visual appearance.

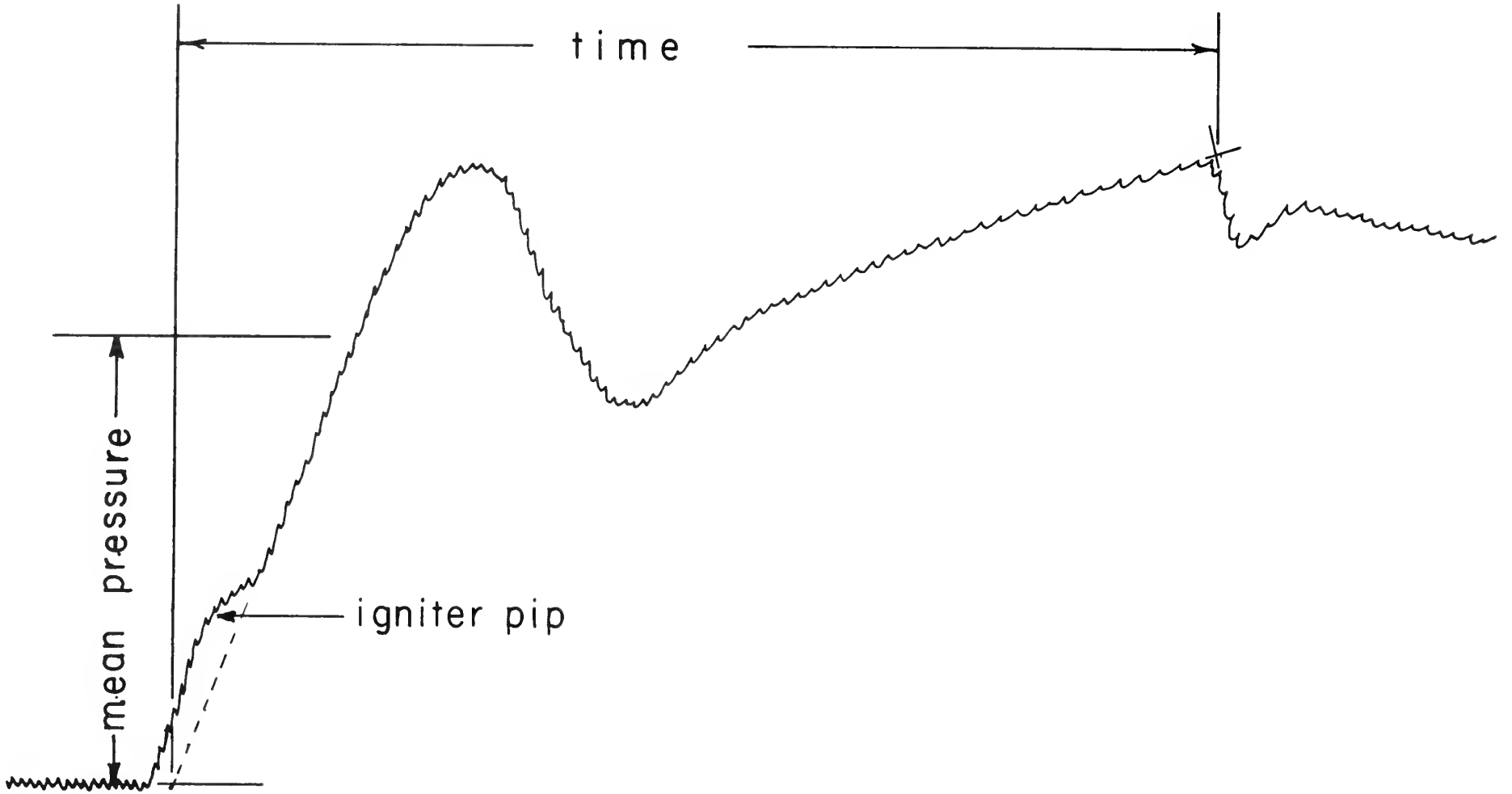

PLATE 6

TYPICAL TIME PRESSURE TRACE

IV. EXPERIMENTAL RESULTS

A. GENERAL

The propellants were burned at two pressures and nine acceleration levels. The base-burning rates and pressure exponents computed from the data compare favorably with values stated by the supplier. The burning rate exponent, n, was determined by using the following equation:

$$r = bP^n$$

B. BASIC NON-ALUMINIZED PROPELLANT

Since this propellant contained no aluminum it was expected to show a burning rate that was independent of acceleration level, that is

$$r/r_o = 1$$

Figures 1, 2 and 3 show the experimentally obtained burning rate ratios at 500 and 1000 psia and the experimentally determined burning-rate exponent respectively. It was observed for the 500 psia data that the burning ratio was fairly constant up to about 200 g's and then fell off rapidly. The 1000 psia runs showed a constant burning rate to 400 g's and dropped less quickly. A possible explanation of this phenomenon is discussed later in this chapter. The results also indicate an apparent increase in burning rate exponent, n, with acceleration.

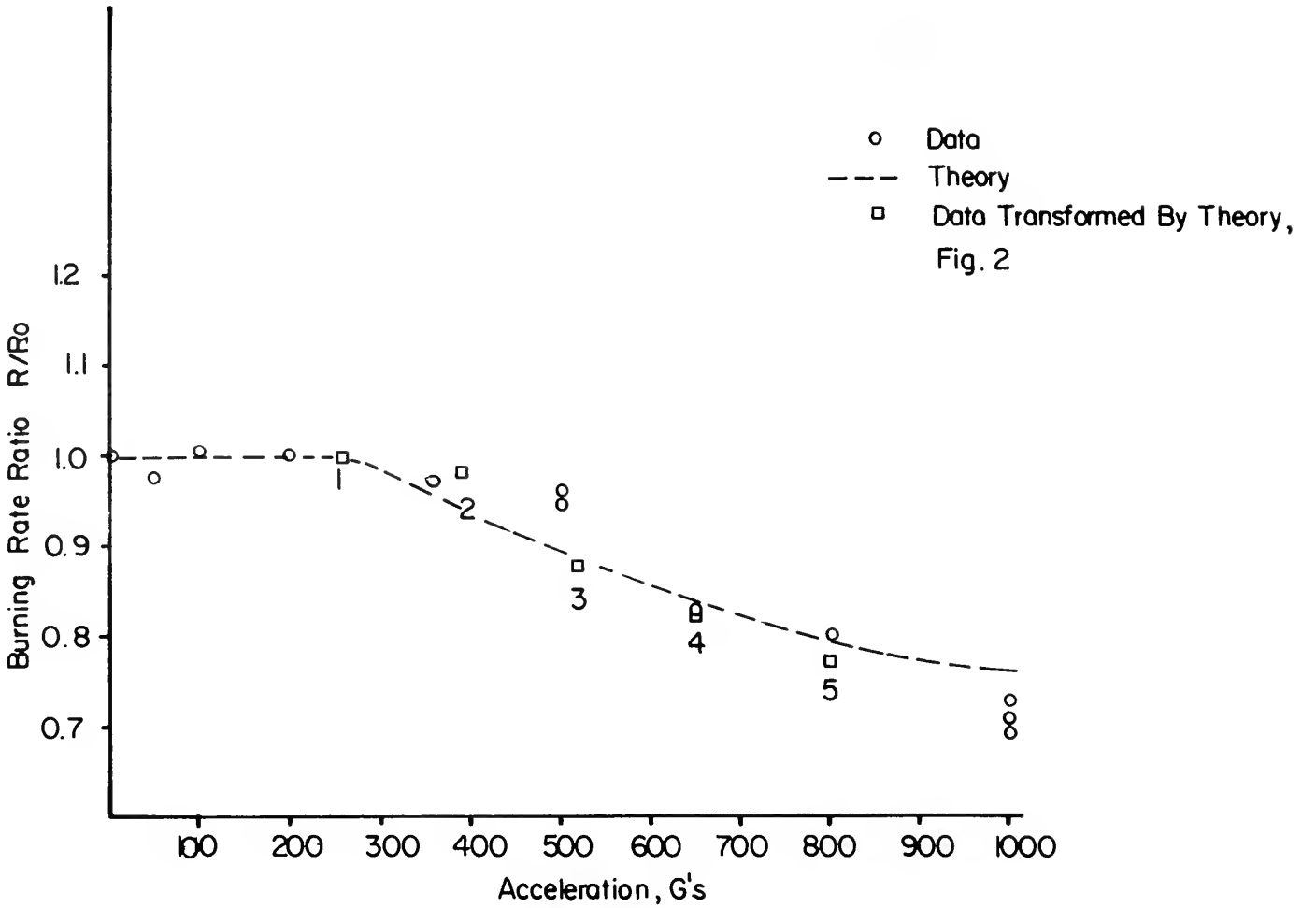

FIGURE 1.

BURNING RATE RATIO VERSUS ACCELERATION FOR NON-ALUMINIZED PROPELLANT AT 500 PSIA

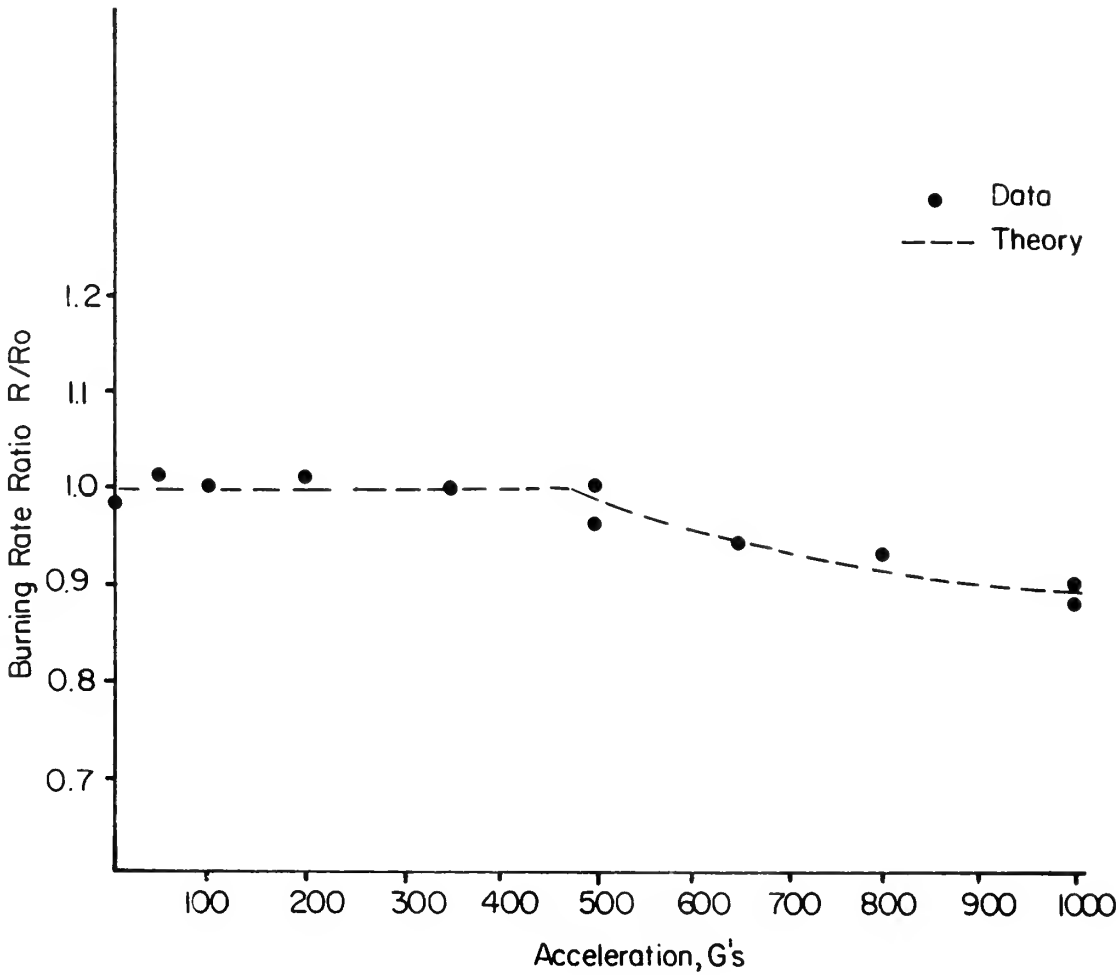

FIGURE 2.

BURNING RATE RATIO VERSUS ACCELERATION FOR NON-ALUMINIZED PROPELLANT AT 1000 PSIA

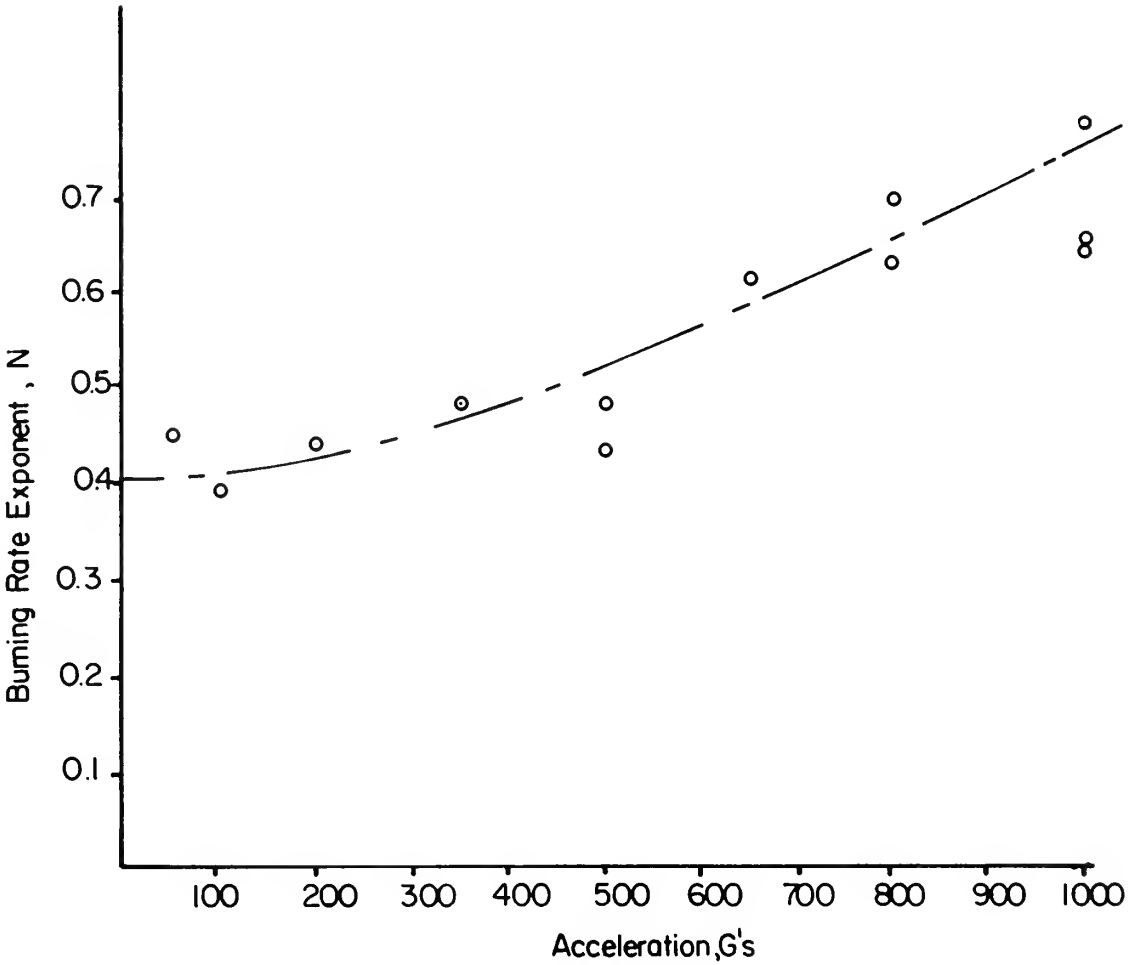

FIGURE 3

BURNING RATE EXPONENT VERSUS ACCELERATION FOR NON—ALUMINIZED PROPELLANT

C. ALUMINIZED PROPELLANT

Figures 4, 5 and 6 show the data obtained for the aluminized propellant at 500 and 1000 psia. The data at 500 psia indicate that the burning rate is roughly constant up to about 500 g's then falls off slightly after that. At 1000 psia the burning increases from the start but is relatively constant between 200 and 500 g's. Above 500 g's the burning rate starts to increase again. A possible explanation for this behavior is advanced below. As with the non-aluminized propellant, n seems to increase with g.

D. RESIDUE

After the firings the cases were checked for residue. The cases that contained the non-aluminized propellant had only a sooty residue. At zero g the aluminized propellant left the same sooty residue. The cases that were run at acceleration showed two kinds of residue. The most common residue was a metallic-looking solid mass, increasing in size with acceleration. Above 800 g's it covered the entire bottom of the case. In several runs however the residue was loose, gray powder weighing much less than the solid residue obtained from other runs at the same acceleration. Figure 7 shows the combined residue data. The crumbly residue data is stared. On cross-checking with the burning rate data there appears to be no difference in the burning rates of samples yielding different residues at the same acceleration levels. It appears that the cause for the difference in the residues

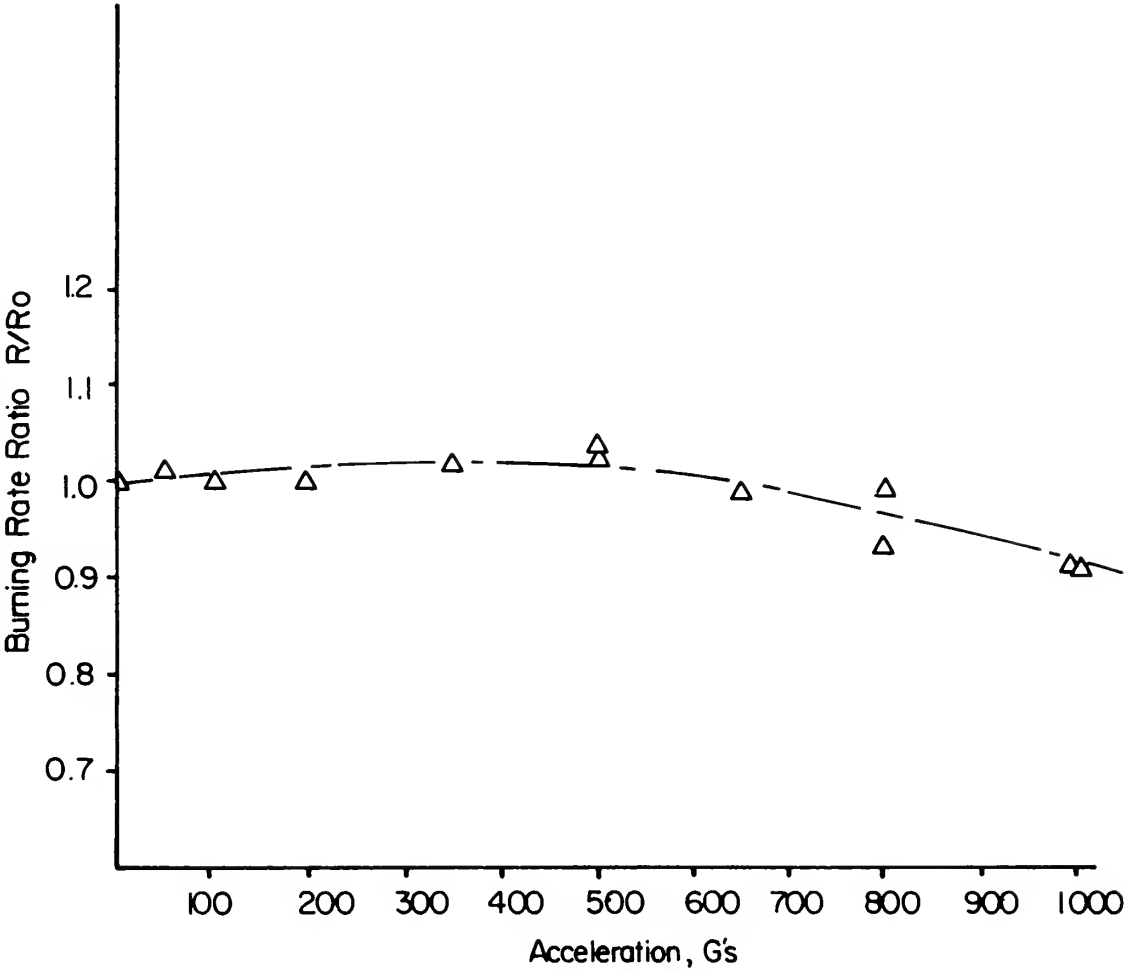

FIGURE 4

BURNING RATE RATIO VERSUS ACCELERATION
FOR ALUMINIZED PROPELLANT AT 500 PSIA

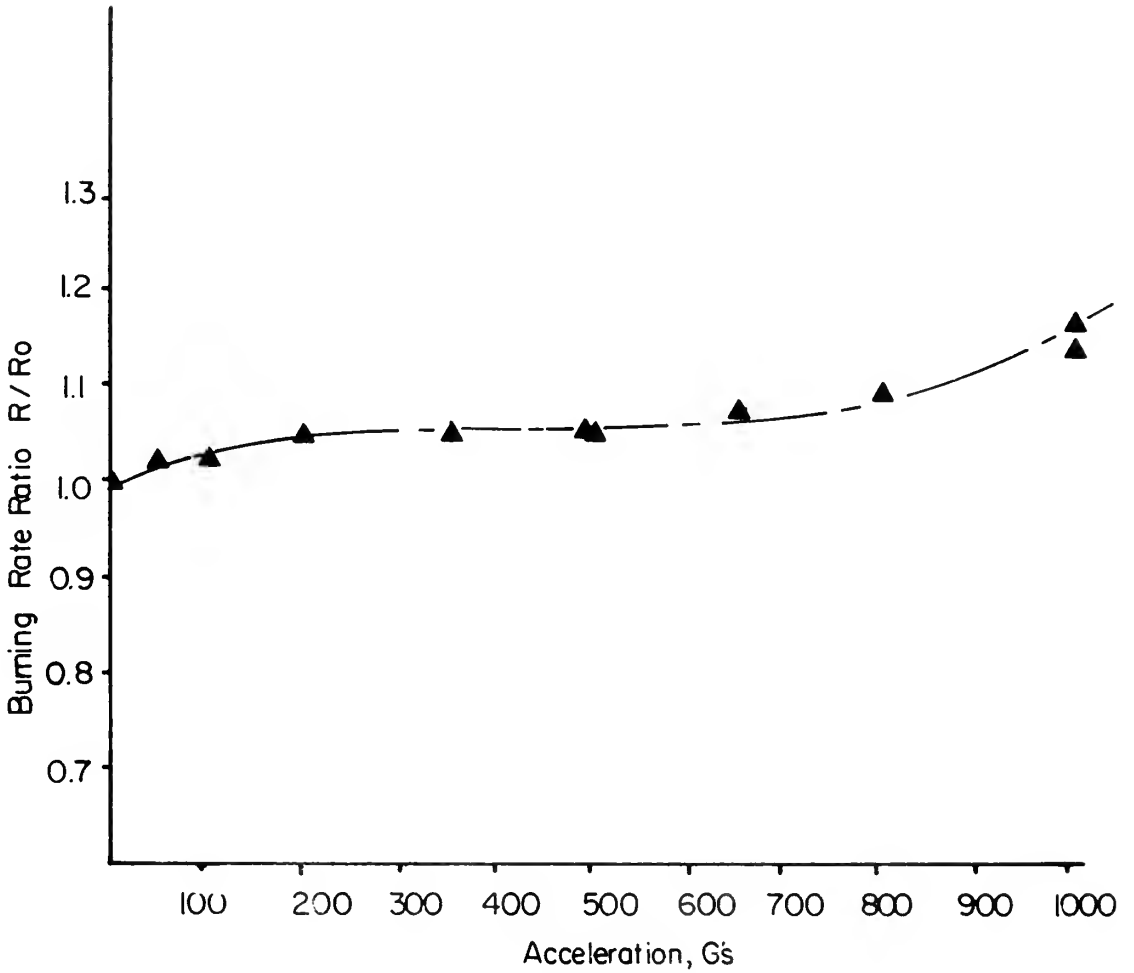

FIGURE 5

BURNING RATE RATIO VERSUS ACCELERATION
FOR ALUMINIZED PROPELLANT AT 1000 PSIA

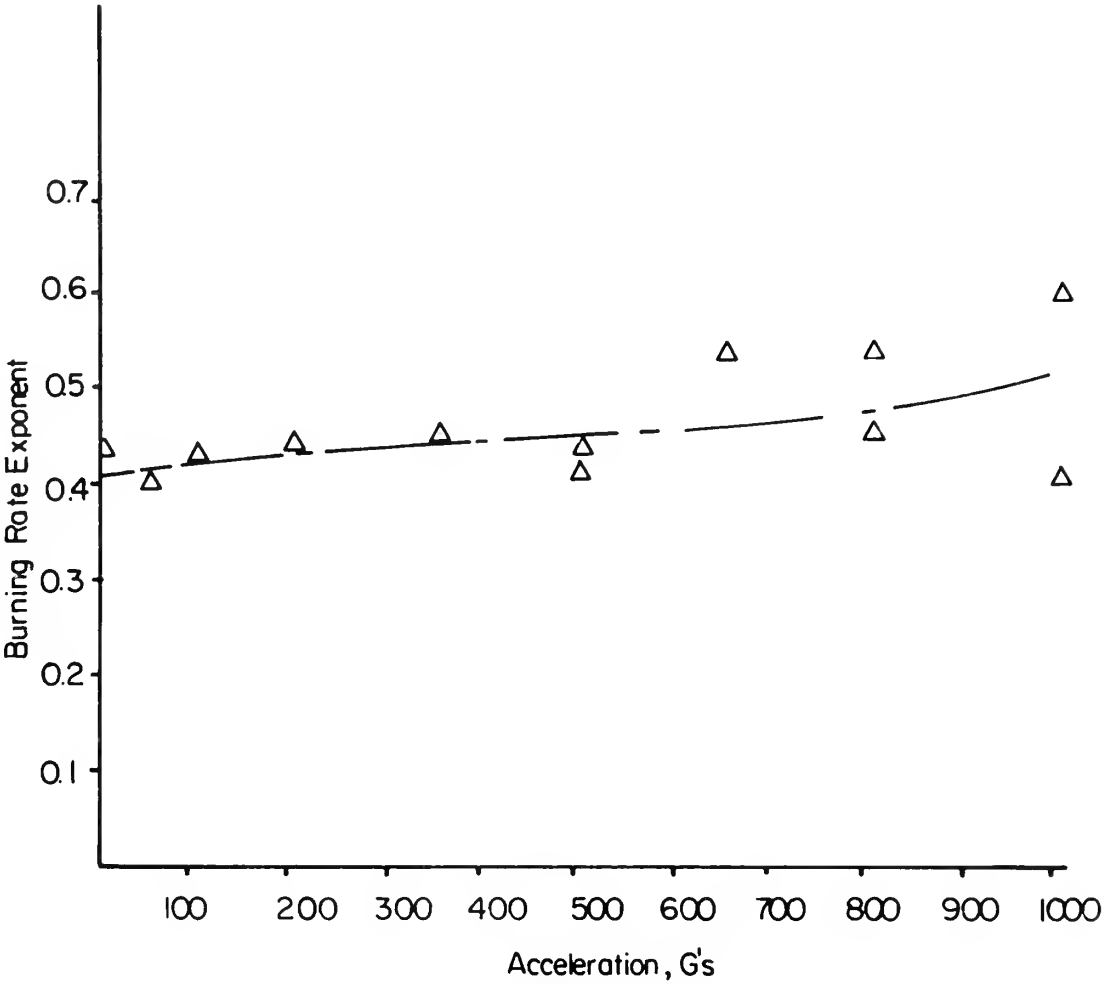

FIGURE 6

BURNING RATE EXPONENT VERSUS ACCELERATION FOR ALUMINIZED PROPELLANT

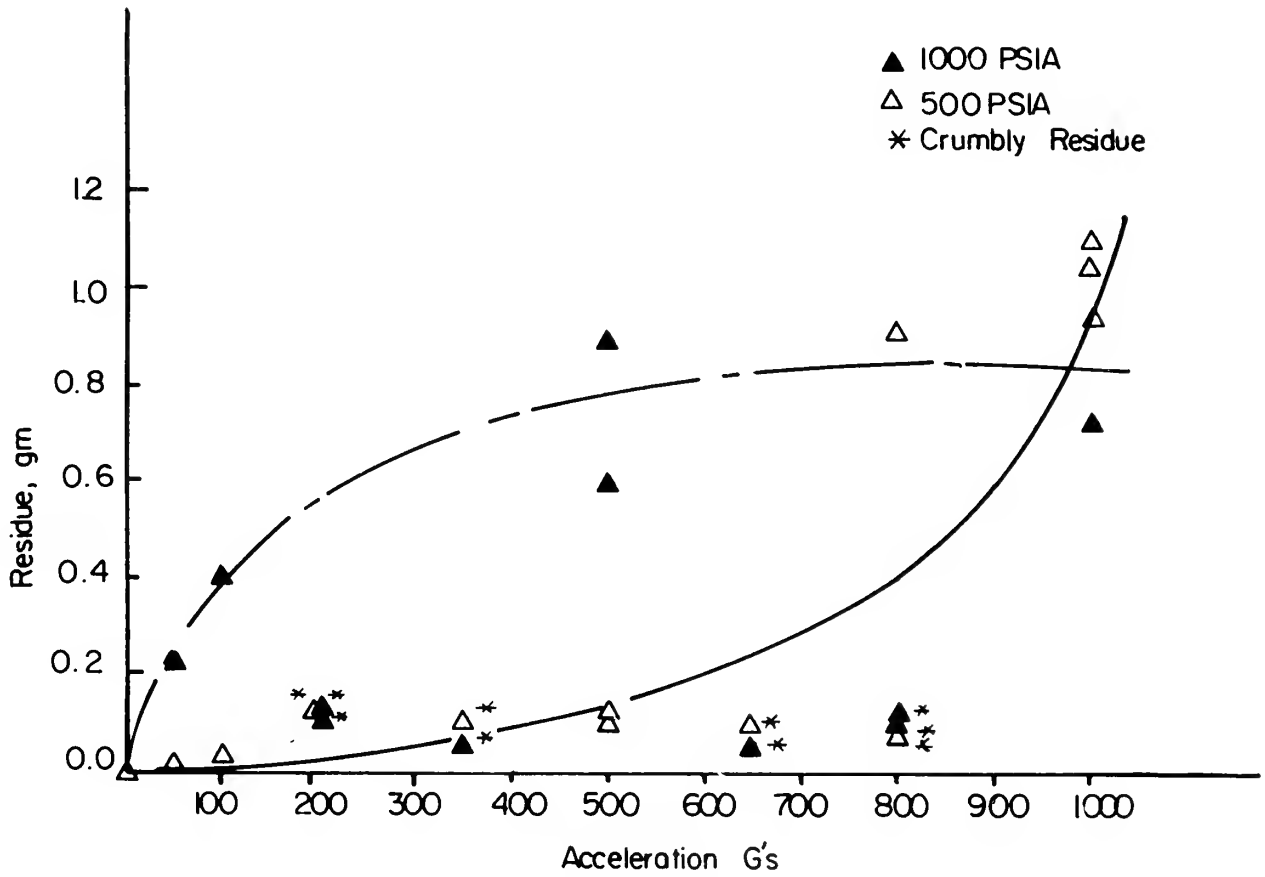

FIGURE 7

2 INCH STRAND RESIDUE VERSUS ACCELERATION FOR ALUMINIZED PROPELLANT

may have occurred after the firings. The solid residues appear to be aluminum oxide held together with aluminum and small quantities of copper. It is interesting to note that in a few cases considerable separation of the aluminum and copper could be observed. Two of the residue samples had a thin layer of material that seemed to be mostly copper coating the bottom. This coating could easily be pulled off intact and was probably a natural separation of the molten slag at the bottom of the case after burn out and not an indication that the copper burned faster through the propellant. It seems probable that nitrate compounds were in the residue. Some of the spent cases had a weak nitric acid smell. At times that the powdery residue was formed these nitrates may have combined with excess moisture in the air (during post-fire storage) to break down the residue.

E. DISCUSSION

The purpose of this study was to isolate the effect of the aluminum on the burning rate augmentation. If the aluminum implemented augmentation and the mechanism responsible for the decrease in the burning rate of the non-aluminized propellant are independent of each other, then the augmentation effect due to the aluminum alone would be the difference in the burning rates of the two propellants. It was therefore necessary to look into the possible cause for the decrease in the non-aluminized burning rates with acceleration.

A review of the theories on double-base burning yielded no terms that could be influenced by acceleration, however, Parr and Crawford [5] mention the existence of small bubbles in the foam zone of extinguished propellants. The foam zone is a semiliquid layer on the surface of the burning propellant. In fact, the foam zone received its name from its bubbly appearance. If bubbles exist in the molten layer of the propellant they would contribute more burning surface . Under 1g conditions these bubbles would be relatively immobile and the resulting surface and bubble area would yield the "normal" or base-burning rate. Under higher accelerations these bubbles will experience a considerable buoyant force. Some of the bubbles might be ejected prematurely from the liquid mass, reducing the total burning surface and thus the net burning rate. The following is a discussion of this proposed model.

The buoyant force on a bubble in static equilibrium in the molten propellant is given by

$$B = \left(\frac{4}{3}\right)\pi r_b^3 (\rho_l - \rho_g) G g = C_1 r_b^3 G \qquad (1)$$

Where r_b is the radius of the bubble and ρ_l and ρ_g are the densities of the liquid and gas respectively. G is the acceleration in g's. The density of the bubble is much smaller than that of the liquid and can be neglected. The liquid is assumed to behave as a Bingham plastic. This means that the fluid will support a maximum shear τ_m with zero strain rate. Above this maximum shear the bubble breaks away and a non-zero strain rate can be set up; i.e., motion.

The maximum static force on a bubble is proportional to the bubble surface area:

$$R = C_2 r_b^2 \tag{2}$$

Equating equations 1 and 2 gives:

$$G C_1 r_c^3 = C_2 r_c^2$$

where r_c is the "critical" radius when the forces are equal. Solving for r_c:

$$r_c = \frac{C_2}{C_1 G} = \frac{C_3}{G} \tag{3}$$

Now all bubbles with $r > r_c$ will be ejected from the foam zone and reduce the burning area. The reduction in area is:

$$\Delta A = -\int_{r_c}^{\infty} \psi_r \, 4\pi r^2 \, dr \tag{4}$$

ψ_r is the number distribution of the bubbles based on r. Researchers have reported decreasing foam zone thickness with increasing pressure. It seems reasonable to assume that the mass in the bubbles remains constant and they simply compress at higher pressures. Therefore the mass distribution function will be assumed independent of pressure and expotentially dependent of mass. Thus:

$$\psi_m = \lambda e^{-\beta m} \tag{5}$$

The mass of the bubble is:

$$m = (4/3) \pi r^3 \rho_g \tag{6}$$

The gas density P_g is:

$$\rho_g = \frac{P}{RT} \tag{7}$$

Thus:

$$m = (4/3)\pi r^3 \frac{P}{RT} \tag{8}$$

solving for r gives:

$$r = \left(\frac{3}{4}\frac{RT}{\pi P} m\right)^{1/3} = C_4 \left(\frac{m}{P}\right)^{1/3} \tag{9}$$

and:

$$dr = \frac{C_4}{3} P^{-1/3} (m)^{-2/3} dm \tag{10}$$

Substituting 9 and 10 into 4 yields:

$$\Delta A = -\int_{m_c}^{\infty} \psi_m \frac{4}{3}\pi \frac{C_4}{P}\left(\frac{3}{4}\frac{RT}{\pi}\right)^{2/3} dm$$

or

$$\Delta A = -\int_{m_c}^{\infty} \frac{C_5}{P} e^{-\beta m} dm \tag{11}$$

Now it is assumed that the burning rate ratio decrease is proportional to the reduction in area or:

$$\frac{\Delta \dot{r}^{\circ}}{\dot{r}_o^{\circ}} = C_6 \Delta A \tag{12}$$

Integrating equation 11 gives:

$$\frac{\Delta \dot{r}^{\circ}}{\dot{r}_o^{\circ}} = -\frac{C_7}{\beta P} e^{-\beta m_c} = -\frac{C_8}{P} e^{-\beta m_c} \tag{13}$$

The value of m_c is readily obtained:

$$m_c = \left(\frac{P}{RT}\right)\frac{4}{3}\pi r_c^3 = C_9 \frac{P}{G^3} \tag{14}$$

14 into 13 gives:

$$\frac{\Delta \dot{r}}{\dot{r}_o} = -\frac{\gamma}{P} \exp\left(-\frac{\alpha P}{G^3}\right)$$

This relatioship for burning rate decrement has two constants γ and α, and it would seem reasonable to expect a particular choice of values for these would yield good agreement with the data. However if the data from one pressure could be transformed into the data from the other without assigning values to the unknown constants, then the model would seem to have some validity. The ratio of the burning rate decrements at different conditions would be

$$\frac{\Delta \dot{r}(@\ P_1, G_1) / \dot{r}_o(@\ P_1)}{\Delta \dot{r}(@\ P_2, G_2) / \dot{r}_o(@\ P_2)} = \left(\frac{P_2}{P_1}\right) \exp -\alpha\left(\frac{P_2}{G_2^3} - \frac{P_1}{G_1^3}\right) \quad (16)$$

if $\frac{P_2}{G_2^3} = \frac{P_1}{G_1^3}$ then the ratio reduces to

$$\left(\frac{\Delta \dot{r}}{\dot{r}_o}\right)_1 \Big/ \left(\frac{\Delta \dot{r}}{\dot{r}_o}\right)_2 = \frac{P_2}{P_1} \quad (17)$$

Since data was taken at 500, and 1000 psia, let $P_1 = 1000$ and $P_2 = 500$ psia. In order for equation 17 to be true $\left(\frac{G_1}{G_2}\right)^3 = 2$. Transforming the data at 1000 psia and 350, 500, 650, 800, and 1000 g's from Figure 2 onto Figure 1 (the numbered squares) yields good agreement. The curves on the figures correspond to $\gamma = 1.3 \times 10^2$ and $\alpha = 2.1 \times 10^5$. Running at additional pressures would help confirm the model.

In order to interpret the data for the aluminized propellant it is necessary to remove the effect of the foam zone. This is done by subtracting the burning rate of the non-aluminized from the burning rate of the aluminized propellant. Figures 8 and **9** show these results. They both demonstrate low augmentation below a critical acceleration. This acceleration corresponds with the acceleration that resulted in signigicant bubble loss at that pressure. After this break point the augmentation increases rapidly. The rate of increase is the same for both pressures, 4%/100 g's. This can possible be explained in the following way.

If the initial size of the aluminum particle is less than the thickness of the foam zone it will remain on the bottom of the foam zone. Since the temperature of the foam zone is less than the melting or ignition temperature of the aluminum it will remain inert unless hot gases can be brought in contact with it. The bubbles contain hot gas but are immobile at low acceleration. Above the critical acceleration where noticeable movement occurs, the aluminum can receive heat from these bubbles and the burning rate would increase.

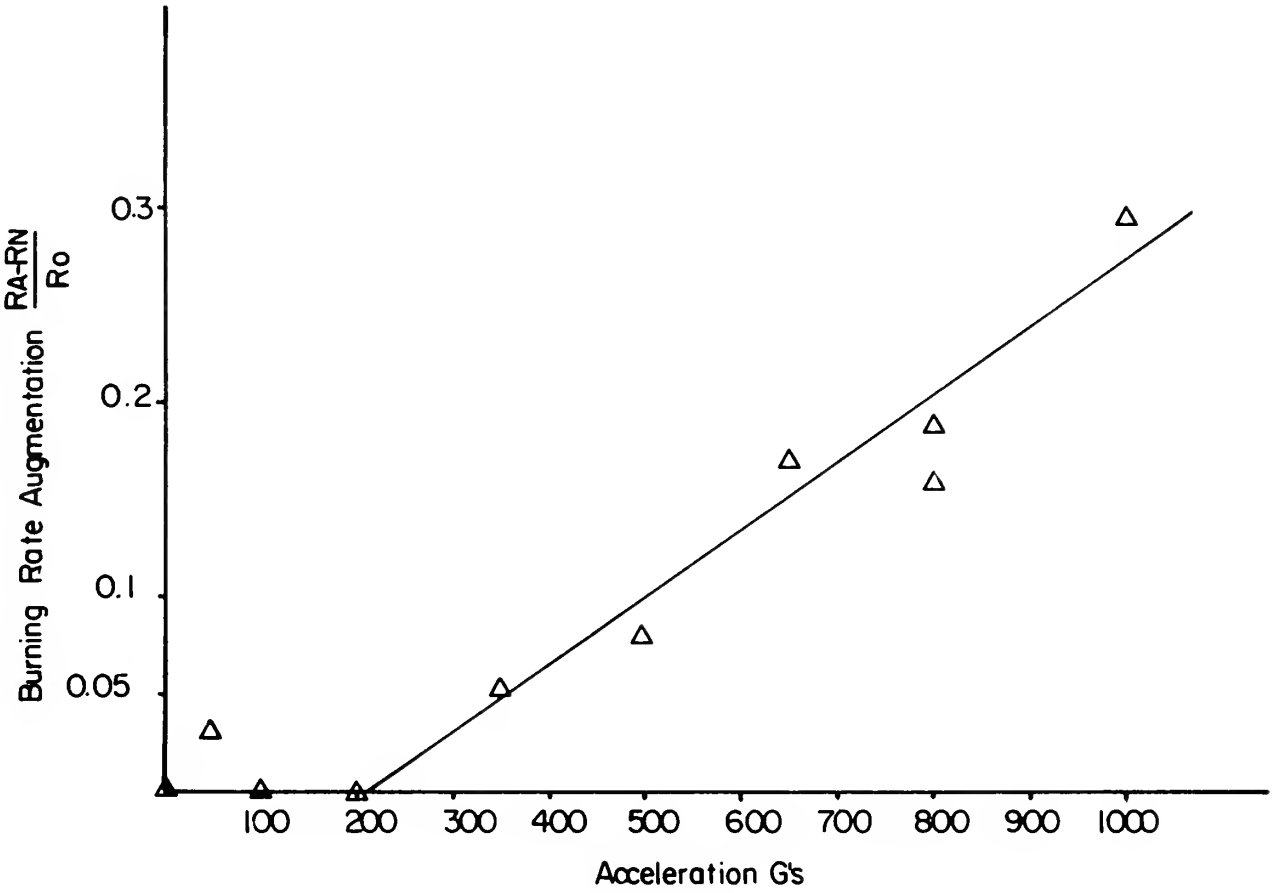

FIGURE 8

BURNING RATE AUGMENTATION VERSUS ACCELERATION AT 500 PSIA

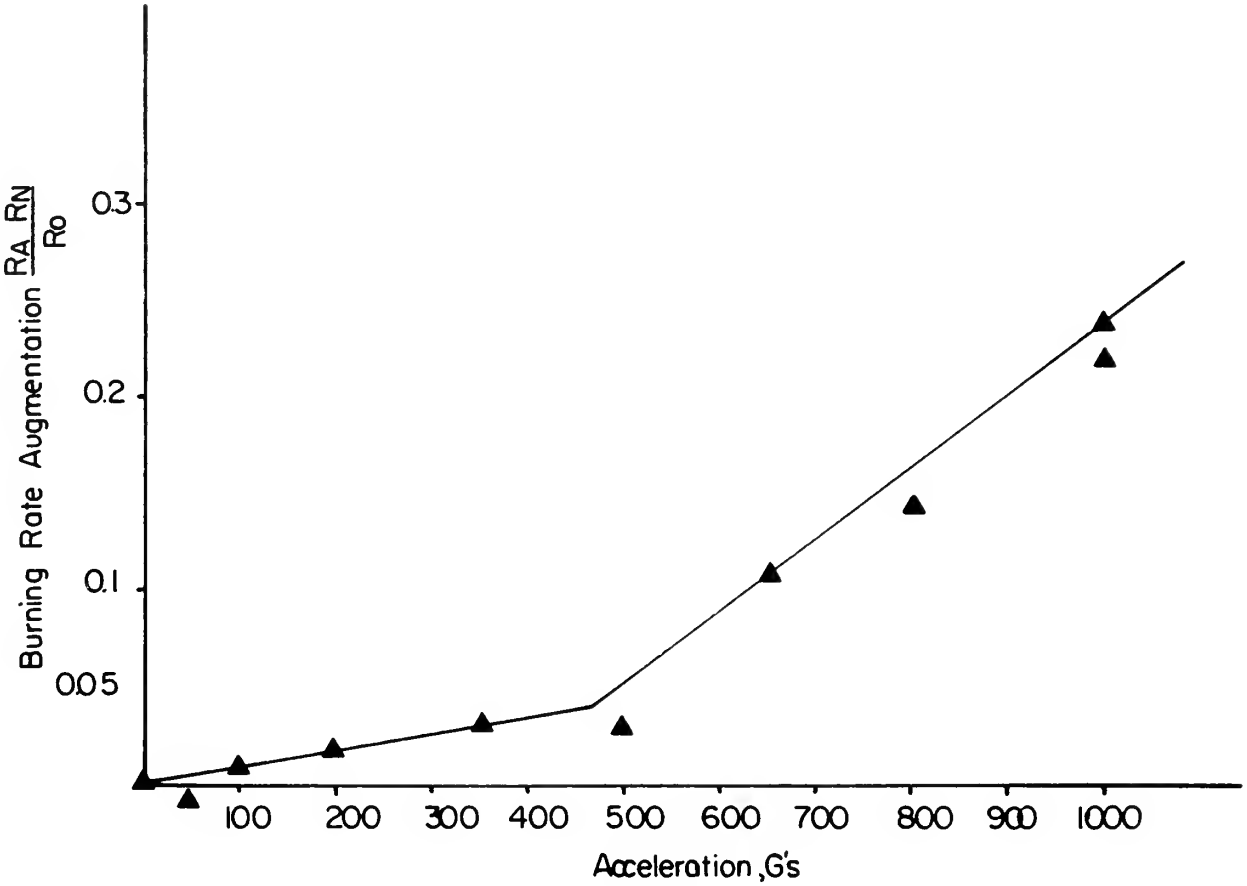

FIGURE 9

BURNING RATE AUGMENTATION VERSUS ACCELERATION AT 1000 PSIA

V. COMPARISON WITH THEORY

A. THEORY OF WILLOUGHBY

Willoughby and coworkers [7] have developed an improved model for the acceleration-produced augmentation due to aluminum. They propose that an aluminum particle resides in the bottom of a pit supported against the g force by the drag of the evolving gases. In their discussion they show that the increase in burning rate could not be accounted for solely by the increased pressure on the propellant just below the particle. They state the main augmentation mechanism is the increased conductive heat transfer from the hot particle to the propellant surface. In going through the heat transfer equations they come up with the following equation for burning rate augmentation.

$$\frac{\dot{r}_a}{\dot{r}_o} \cong 2\left[\frac{r_s}{a}\left(\frac{\rho_p P_c \alpha}{r_s}\right)^{1/4} \frac{K'}{\rho_s \dot{r}_o (1-W)} - 0.2\right] + 1$$

Where a is the semimajor axis of the elliptical particle P_c is the combustion pressure, ρ_s is the density of the solid propellant. α is the acceleration, r_s the equivalent spherical radius of the particle, ρ_p the density of the particle, W the volume fraction of the aluminum and K^1 an unknown constant. This equation predicts a 1/4 power dependence of augmentation on acceleration, if the particle size does not depend on acceleration. The particle size however may depend on acceleration and according to Sturm [1] may even depend on time.

Comparing the aluminum data from the present study with the Willoughby model indicates little or no agreement. Figures 10 and 11 show the augmentation resulting from the aluminum addition increasing as the second power of the acceleration.

It should be pointed out, however, that Willoughby's model was based on a propellant with a solid-gas reaction at the surface and cannot account for the presence of a liquid phase. Thus no direct comparison can fairly be made between the data obtained in the present investigation and the model.

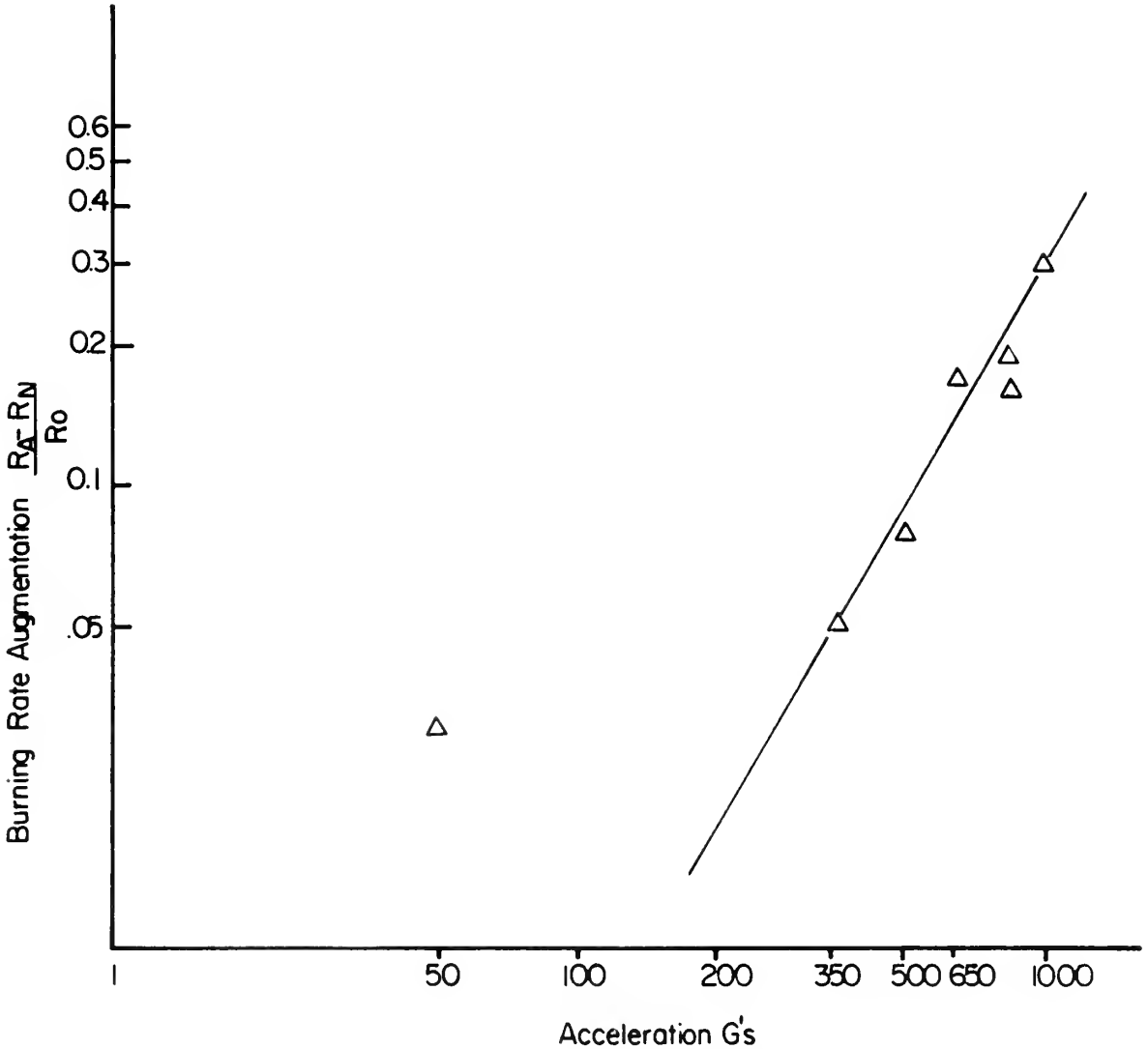

FIGURE 10

LOG PLOT OF BURNING RATE AUGMENTATION VERSUS ACCELERATION AT 500 PSIA

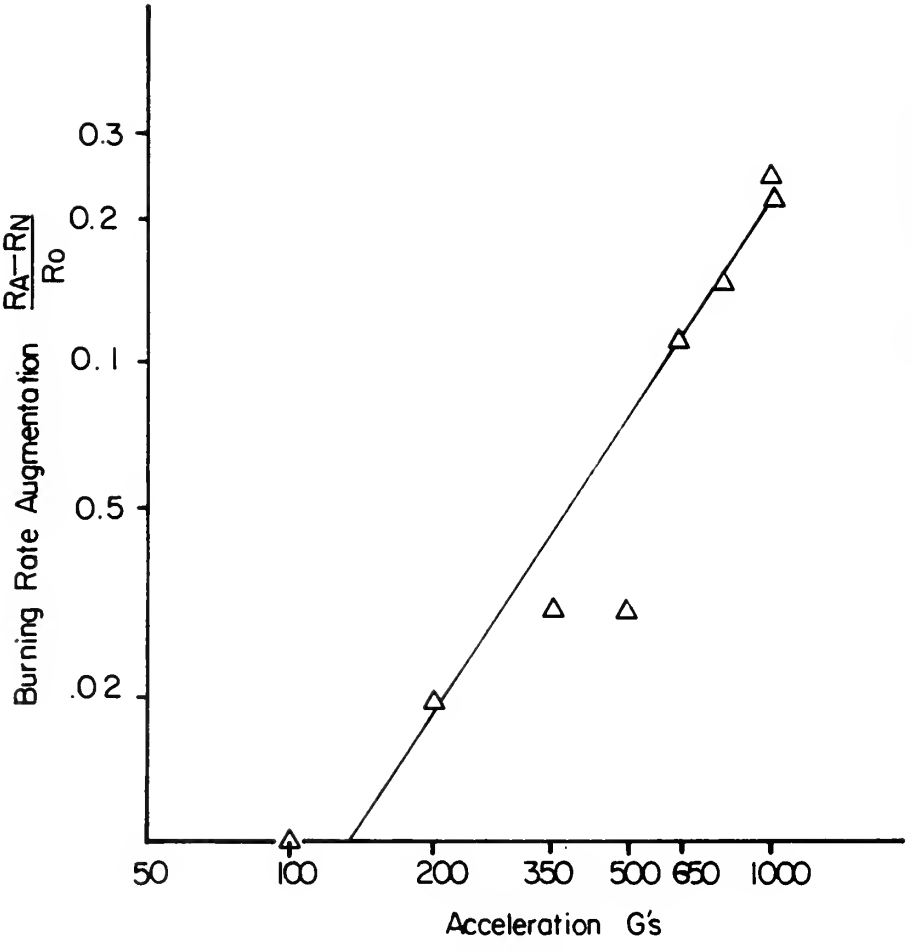

FIGURE 11

LOG PLOT OF BURNING RATE AUGMENTATION VERSUS ACCELERATION AT 500 PSIA

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The burning rate of a double-base propellant is definitely affected by acceleration. Without aluminum the effect is a decrease in the burning rate. An analytical model proposed indicates that bubbles in the foam zone are responsible for this decrease.

The aluminum increases the burning rate over that of the basic propellant at the same conditions in a manner not predicted by previous models. This appears to be due to the presence of the liquid region on the surface of the propellant.

B. RECOMMENDATIONS

Experiments should be conducted at additional pressures to evaluate the model proposed in this study. They should concentrate on the foam zone with high-resolution photographic work to determine the extent of the foam zone at various accelerations and pressures. A study of extinguished propellant samples run at various pressures and accelerations would also be helpful.

After the burning mechanism of the non-aluminized double base is better understood then a study can be profitably initiated to examine the effect of the aluminum and an adequate model advanced.

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13. ABSTRACT

Double base rocket propellants with and without aluminum were burned in a centrifuge at two pressures and nine accelerations. The burning rates were measured to isolate the effect of the aluminum. The burning rate of the non-aluminized propellant was found to vary with acceleration and a model was advanced. The addition to aluminum causes an increase in burning rate at higher accelerations and a possible mechanism is discussed.

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